Fitness tracking reveals task-specific associations between memory, mental health, and exercise

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Abstract

Physical exercise can benefit both physical and mental well-being. Different forms of exercise (i.e., aerobic versus anaerobic; running versus walking versus swimming versus yoga; high-intensity interval training versus endurance workouts; etc.) impact physical fitness in different ways. For example, running may substantially impact leg and heart strength but only moderately impact arm strength. We hypothesized that the mental benefits of exercise might be similarly differentiated. We focused specifically on how different forms of exercise might related to different aspects of memory and mental health. To test our hypothesis, we collected nearly a century's worth of fitness data (in aggregate). We then asked participants to fill out surveys asking them to self-report on different aspects of their mental health. We also asked participants to engage in a battery of memory tasks that tested their short and long term episodic, semantic, and spatial memory. We found that participants with similar exercise habits and fitness profiles tended to also exhibit similar mental health and task performance profiles.

Introduction

Engaging in physical activity (exercise) can improve our physical fitness by increasing muscle strength (Crane et al., 2013; Knuttgen, 2007; Lindh, 1979; Rogers and Evans, 1993), increasing bone density (Bassey and Ramsdale, 1994; Chilibeck et al., 2012; Layne and Nelson, 1999), increasing cardiovascular performance (Maiorana et al., 2000; Pollock et al., 2000), increasing lung capacity (Lazovic-Popovic et al., 2016) (although see Roman et al., 2016), increasing endurance (Wilmore and Knuttgen, 2003), and more. Exercise can also improve mental health (Basso and Suzuki, 2017; Callaghan, 2004; Deslandes et al., 2009; Mikkelsen et al., 2017; Paluska and Schwenk, 2000; Raglin, 1990; Taylor et al., 1985) and cognitive performance (Basso and Suzuki, 2017; Brisswalter et al., 2002; Chang et al., 2012; Etnier et al., 2006).

The physical benefits of exercise can be explained by stress-responses of the affected body tissues. For example, skeletal muscles that are taxed during exercise exhibit stress responses (Morton et al., 2009) that can in turn affect their growth or atrophy (Schiaffino et al., 2013). By comparison, the benefits of exercise on mental health are less direct. For example, one hypothesis is that exercise leads to specific physiological changes, such as increased aminergic synaptic transmission and endorphin release, which in turn act on neurotransmitters in the brain (Paluska and Schwenk, 2000).

Speculatively, if different exercise regimens lead to different neurophysiological responses, one might be able to map out a spectrum of signalling and transduction pathways that are impacted by a given type, duration, and intensity of exercise in each brain region. For example, prior work has shown that exercise increases acetylcholine levels, starting in the vicinity of the exercised muscles (Shoemaker et al., 1997). Acetylcholine is thought to play an important role in memory formation (Palacios-Filardo et al., 2021, e.g., by modulating specific synaptic inputs from entorhinal cortex to the hippocampus, albeit in rodents;). Given the central role of these medial temporal lobe structures play in memory, changes in acetylcholine might lead to specific changes in memory formation and retrieval.

In the present study, we hypothesize that (a) different exercise regimens will have different, quantifiable impacts on cognitive performance and mental health, and that (b) these impacts will be consistant across individuals. To this end, we collected a year of fitness tracking data from each of 113 participants. We then asked each participant to fill out a brief survey in which they self-evaluated several aspects of their mental health. Finally, we ran each participant through a battery of memory tasks, which we used to evaluate their memory performance along several dimensions. We examined the data for potential associations between memory, mental health, and exercise.

Results

- exploratory analysis (correlations)
  - Memory-memory
  - fitness-fitness
  - survey-survey
  - (fitness + survey)-memory
- predictive analysis (regressions)
  - Predict memory performance on held-out task from other tasks
  - Predict memory performance on each task using fitness data
  - Predict memory performance on each task using survey data
- Reverse correlations: look at recent changes versus baseline trends
  - Fitness profile that predicts performance on each task (barplots + timelines)
  - Fitness profile for each survey demographic (barplots + timelines)
    - Select out mental health demographics (based on meds, stress levels)

Discussion

- summarize key findings
- correlation versus causation
- what can vs. can't we know? we can identify correlations, but not causal direction– e.g. we cannot know whether exercise *causes* mental changes versus whether people with particular neural profiles might tend to engage in particular exercise behaviors. that being said, we *can* separate out baseline tendencies (e.g., how people tend to exercise in general) versus recent changes (e.g., how they happened to have exercised prior to the experiment).
- related work (exercise/memory, exercise/mental health), what this study adds
- future direction: towards customized physical exercise recommendation engine for optimizing mental health and mental fitness

Methods

We ran an online experiment using the Amazon Mechanical Turk platform. We collected data about each participant's fitness and exercise habits, a variety of self-reported measures concerning their mental health, and about their performance on a battery of memory tasks. We mined the dataset for potential associations between memory, mental health, and exercise.

Experiment

Participants

We recruited experimental participants by posting our experiment as a Human Intelligence Task (HIT) on the Amazon Mechanical Turk platform. We limited participation to Mechanical Turk Workers who had been assigned a "Masters" designation on the platform, given to workers who score highly across several metrics on a large number of HITs, according to a proprietary algorithm managed by Amazon. We further limited our participant pool to participants who self-reported that they were fluent in English and regularly used a Fitbit fitness tracker device. A total of 160 workers accepted our HIT in order to participate in our experiment. Of these, we excluded all participants who failed to log into their Fitbit account (giving us access to their anonymized fitness tracking data), encountered technical issues (e.g., by accessing the HIT using an incompatible browser, device, or operating system), or who ended their participation prematurely, before completing the full study. In all, 113 participants remained that contributed usable data to the study.

For their participation, workers received a base payment of \$5 per hour (computed in 15 minute increments, rounded up to the nearest 15 minutes), plus an additional performance-based bonus of up to \$5. Our recruitment procedure and study protocol were approved by Dartmouth's Committee for the Protection of Human Subjects.

Gender, age, and race. Of the 113 participants who contributed usable data, 77 reported their gender as female, 35 as male, and 1 chose not to report their gender. Participants ranged in age from 19–68 years old (25^{th} percentile: 28.25 years; 50^{th} percentile: 32 years; 75^{th} percentile: 38 years). Participants reported their race as White (90 participants), Black or African American (11 participants), Asian (7 participants), Other (4 participants), and American Indian or Alaska Native (3 participants). One participant opted not to report their race.

Languages. All participants reported that they were fluent in either 1 and 2 languages (25^{th} percentile: 1; 50^{th} percentile: 1; 75^{th} percentile: 1), and that they were "familiar" with between 1 and 11 languages (25^{th} percentile: 1; 50^{th} percentile: 2; 75^{th} percentile: 3).

Reported medical conditions and medications. Participants reported having and/or taking medications pertaining to the following medical conditions: anxiety or depression (4 participants), recent head injury (2 participants), high blood pressure (1 participant), bipolar (1 participant), hypothyroidism (1 participant), and other unspecified medications (1 participant). Participants reported their current and typical stress levels on a Likert scale as very relaxed (-2), a little relaxed (-1), neutral (0), a little stressed (1), or very stressed (2). The "current" stress level reflected participants' stress at the time they participated in the experiment. Their responses ranged from -2 to 2 (current stress: 25^{th} percentile: -2; 50^{th} percentile: -1; 75^{th} percentile: 1; typical stress: 25^{th} percentile: 0; 50^{th} percentile: 1; 75^{th} percentile: 1). Participants also reported their current level of alertness on a Likert scale as very sluggish (-2), a little sluggish (-1), neutral (0), a little alert (1), or very alert (2). Their responses ranged from -2 to 2 (25^{th} percentile: 0; 50^{th} percentile: 1; 75^{th} percentile: 2). Nearly all (111 out of 113) participants reported that they had normal color vision, and 15 participants reported uncorrected visual impairments (including dyslexia and uncorrected near- or far-sightedness).

Residence and level of education. Participants reported their residence as being located in the suburbs (36 participants), a large city (30 participants), a small city (23 participants), rural (14 participants), or a small town (10 participants). Participants reported their level of education as follows: College graduate (42 participants), Master's degree (23 participants), Some college (21 participants), High school graduate (9 participants), Associate's degree (8 participants), Other graduate or professional school (5 participants), Some graduate training (3 participants), or Doctorate (2 participants).

Reported water and coffee intake. Participants reported the number of cups of water and coffee they had consumed prior to accepting the HIT. Water consumption ranged from 0–6 cups (25^{th} percentile: 1; 50^{th} percentile: 3; 75^{th} percentile: 4). Coffee consumption ranged from 0–4 cups (25^{th} percentile: 0; 50^{th} percentile: 1; 75^{th} percentile: 2).

Tasks

Upon accepting the HIT posted on Mechanical Turk, the worker was directed to read and fill out a screening and consent form, and to share access to their anonymized Fitbit data via their Fitbit account. After consenting to participant and successfully sharing their Fitbit data, participants filled out a survey and then engaged in a series of memory tasks (Fig. 1). All stimuli and code for running the full Mechanical Turk experiment may be found here.

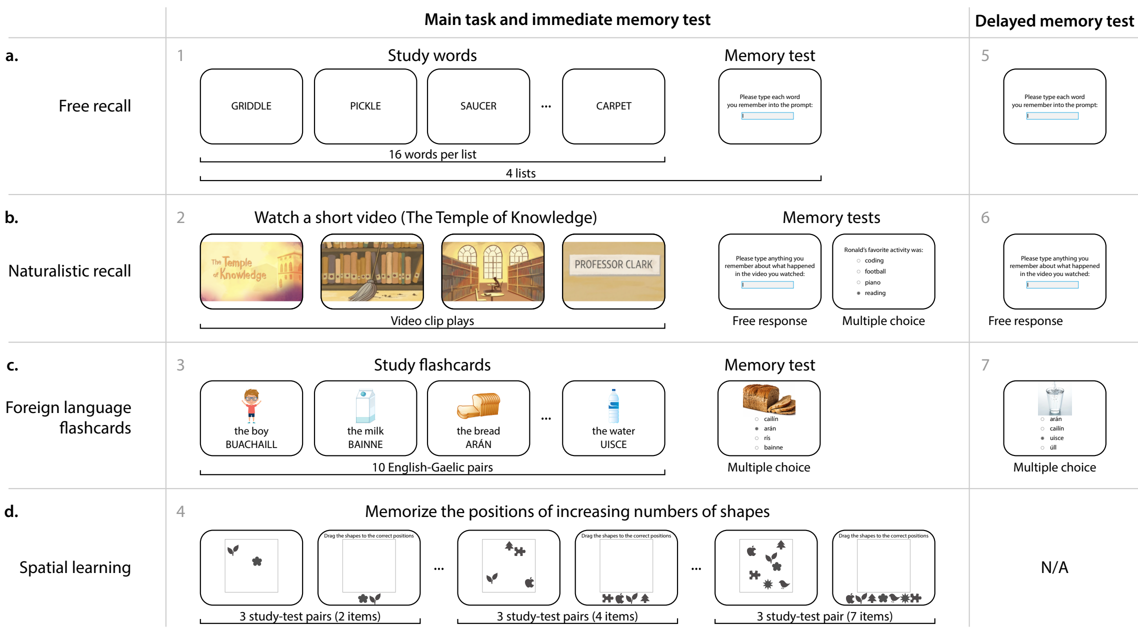

Figure 1: **Battery of memory tasks. a. Free recall.** Participants study 16 words (presented one at a time), followed by an immediate memory test where they type each word they remember from the just-studied list. In the delayed memory test, participants type any words they remember studying, from any list. **b. Naturalistic recall.** Participants watch a brief video, followed by two immediate memory tests. The first test asks participants to write out what happened in the video. The second test has participants answer a series of multiple choice questions about the conceptual content of the video. In the delayed memory test, participants (again) write out what happened in the video. **c. Foreign language flashcards.** Participants study a sequence of 10 English-Gailic word pairs, each presented with an illustration of the given word. During an immediate memory test, participants perform a multiple choice test where they select the Gaelic word that corresponds to the given photograph. During the delayed memory test, participants perform a second multiple choice test, where they select the Gaelic word that corresponds to each of a new set of photographs. **d. Spatial learning.** In each trial, participants study a set of randomly positioned shapes. Next, the shapes' positions are altered, and participants are asked to drag the shapes back to their previous positions. **All panels.** The gray numbers denote the order in which participants experienced each task or test.

Survey questions. We collected the following demographic information from each participant: their birth year, gender, highest (academic) degree achieved, race, language fluency, and language familiarity. We also collected information about participants' health and wellness, including about their vision, alertness, stress, sleep, coffee and water consumption, location of their residence, activity typically required for their job, and exercise habits.

Free recall (Fig. 1a). Participants studied a sequence of four word lists, each comprising 16 words. After studying each list, participants received an immediate memory test, whereby they were asked to type (one word at a time) any words they remembered from the just-studied list, in any order.

Words were presented for 2 s each, in black text on a white background, followed by a 2 s blank (white) screen. After the final 2 s pause, participants were given 90 s to type in as many words as they could remember, in any order. The memory test was constructed such that the participant could only see the text of the current word they were typing; when they pressed any non-letter key, the current word was submitted and the text box they were typing in was cleared. This was intended to prevent participants from retroactively editing their previous responses.

The word lists participants studied were drawn from the categorized lists reported in Ziman et al. (2018). Each participant was assigned four unique randomly chosen lists (in a randomized order), selected from a full set of 16 lists. Each chosen list was then randomly shuffled before presenting the words to the participants.

Participants also performed a final delayed memory test where they were given 180 s to type out any words they remembered from *any* of the 4 lists they had studied.

Recalled words within an edit distance of 2 (i.e., a Levenshtein Distance less than or equal to 2) of any word in the wordpool were "autocorrected" to their nearest match. We also manually corrected clear typos or mispellings by hand (e.g., we corrected "hippoptumas" to "hippopotamus", "zucinni" to "zucchini", and so on). Finally, we lemmatized each submitted word to match the plurality of the matching wordpool word (e.g., "bongo" was corrected to "bongos", and so on). After applying these corrections, any submitted words that matched words presented on the just-studied list were tagged as "correct" recalls, and any non-matching words were discarded as "errors." Because participants were not allowed to edit the text they entered, we chose not to analyze these putative "errors," since we could not distinguish typos from true misrememberings.

Naturalistic recall (Fig. 1b). Participants watched a 2.5 minute video clip entitled "The Temple of Knowledge." The video comprises an animated story told to StoryCorps by Ronald Clark, who was interviewed by his daughter, Jamilah Clark. The narrator (Ronald) discusses growing up living in an apartment over Washington Heights branch of the New York Public Library, where his father worked as a custodian during the 1940s.

After watching the video clip, participants were asked to type out anything they remembered about what happened in the video. They typed their responses into a text box, one sentence at a time. When the participant pressed the return key or typed any final punctuation mark (".", "!", or "?") the text currently entered into the box was "submitted" and added to their transcript, and the text box was cleared to prevent further editing of any already-submitted text. This was intended to prevent participants from retroactively editing their previous responses. Participants were given up to 10 minutes to enter their responses. After 4 minutes participants were given the option of ending the response period early, e.g., if they felt they had finished entering all of the information they remembered. Each participant's transcript was constructed from their submitted responses by combining the sentences into a single document and removing extraneous whitespace characters.

Following this 4–10 minute free response period, participants were given a series of 10 multiple choice questions about the conceptual content of the story. All participants received the same questions, in the same order.

Participants also performed a final delayed memory test, where they carried out the free response recall task a second time, near the end of the testing session. This resulted in a second transcript, for each participant.

Foreign language flashcards (Fig. 1c). Participants studied a series of 10 English-Gaelic word pairs in a randomized order. We selected the Gaelic language both for its relatively small number of native speakers and for its dissimilarity to other commonly spoken languages amongst Mechanical

Turk Workers. We verified (via self report) that all of our participants were fluent in English and that they were neither fluent nor familiar with Gaelic.

Each word's "flashcard" comprised a cartoon depicting the given word, the English word or phrase in lowercase text (e.g., "the boy"), and the Gaelic word or phrase in uppercase text (e.g., "BUACHAILL"). Each flashcard was displayed for 4 s, followed by a 3 s interval (during which the screen was cleared) prior to the next flashcard presentation.

After studying all 10 flashcards, participants were given a multiple choice memory test where they were shown a series of novel photographs, each depicting one of the 10 words they had learned. They were asked to select which (of 4 unique options) Gaelic word went with the given picture. The 3 incorrect options were selected at random (with replacement across trials), and the order in which the choices appeared to the participant were also randomized. Each of the 10 words they had learned were tested exactly once.

Participants also performed a final delayed memory test, where they were given a second set of 10 questions (again, one per word they had studied). For this second set of questions participants were prompted with a new set of novel photographs, and new randomly chosen incorrect choices for each question. Each of the 10 original words they had learned were (again) tested exactly once during this final memory test.

Spatial learning (Fig. 1d). Participants performed a series of study-test trials where they memorized the onscreen spatial locations of two or more shapes. During the study phrase of each trial, a set of shapes appeared on the screen for 10 s, followed by 2 s of blank (white) screen. During the test phase of each trial, the same shapes appeared onscreen again, but this time they were vertically aligned and sorted horizontally in a random order. Participants were instructed to drag (using the mouse) each shape to its studied position, and then to click a button to indicate that the placements were complete.

In different study-test trials, participants learned the locations of different numbers of shapes (always drawn from the same pool of 7 unique shapes, where each shape appeared at most one time per trial). They first performed three trials where they learned the locations of 2 shapes; next three trials where they learned the locations of 3 shapes; and so on until their last three trials, where (during each trial) they learned the locations of 7 shapes. All told, each participant performed 18 study-test trials of this spatial learning task (3 trials for each of 2, 3, 4, 5, 6, and 7 shapes).

Fitness tracking using Fitbit devices

Processing Fitbit data

Raw metrics.

Comparing recent versus baseline measurements.

Exploratory correlation analyses

Imputation and interpolation of missing data.

Regression-based prediction analyses

Reverse correlation analyses

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Data and code availability

All analysis code and data used in the present manuscript may be found here.

Author contributions

Concept: J.R.M. Experiment implementation and data collection: G.M.N. Analyses: G.M.N., E.C., P.C.F., and J.R.M. Writing: J.R.M.

Competing interests

The authors declare no competing interests.

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